CIS 700: Interactive Fiction and Text Generation

Search and Planning

AIMA Chapters 3 and 7

Problem-Solving Agents

A problem-solving agent must **plan**.

The computational process that it undertakes is called **search**.

It will consider a **sequence of actions** that form a **path** to a **goal state**.

Such a sequence is called a **solution.**

1. take pole
2. go out
3. go south
4. catch fish with pole
5. go north
6. pick rose
7. go north
8. go up
9. get branch
10. go down
11. go east
12. give the troll the fish
13. go east
14. hit guard with branch
15. get key
16. go east
17. get candle
18. go west
19. go down
20. light lamp
21. go down
22. light candle
23. read runes
24. get crown
25. go up
26. go up
27. go up
28. unlock door
29. go up
30. give rose to the princess
31. propose to the princess
32. down
33. down
34. east
35. east
36. wear crown
37. sit on throne

Review of Search Problems

AIMA 3.1-3.3

Formal Definition of a Search Problem

1. **States:** a set **S**
2. An **initial state** $s_i \in S$
3. **Actions:** a set **A**

   ∀ s Actions(s) = the set of actions that can be executed in **s**.
4. **Transition Model: ∀ s∀ a∈Actions(s)** **Result(s, a)** → $\mathbf{s_r}$

   $\mathbf{s_r}$ is called a successor of **s**

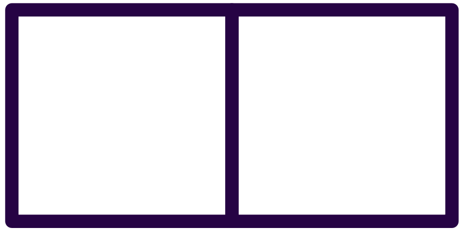
   $\{\mathbf{s_i}\} \cup$ **Successors**$(\mathbf{s_i})$***** = state space
5. **Path cost** (Performance Measure): Must be additive, e.g. sum of distances, number of actions executed, …

   c(x,a,y) is the step cost, assumed ≥ 0

   - (where action **a** goes from state **x** to state **y**)
6. **Goal test: Goal(s)**

   s is a goal state if **Goal(s)** is true. Can be implicit, e.g. **checkmate(s)**

Vacuum World



States: A state of the world says which objects are in which cells.

In a simple two cell version,

- the agent can be in one cell at a time
- each cell can have dirt or not

2 positions for agent * 2^2 possibilities for dirt = 8 states.

With n cells, there are $n*2^n$ states.

Vacuum World

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2 positions for agent * 2^2 possibilities for dirt = 8 states.

With n cells, there are $n * 2^n$ states.

Vacuum World

Goal states: States where everything is clean.

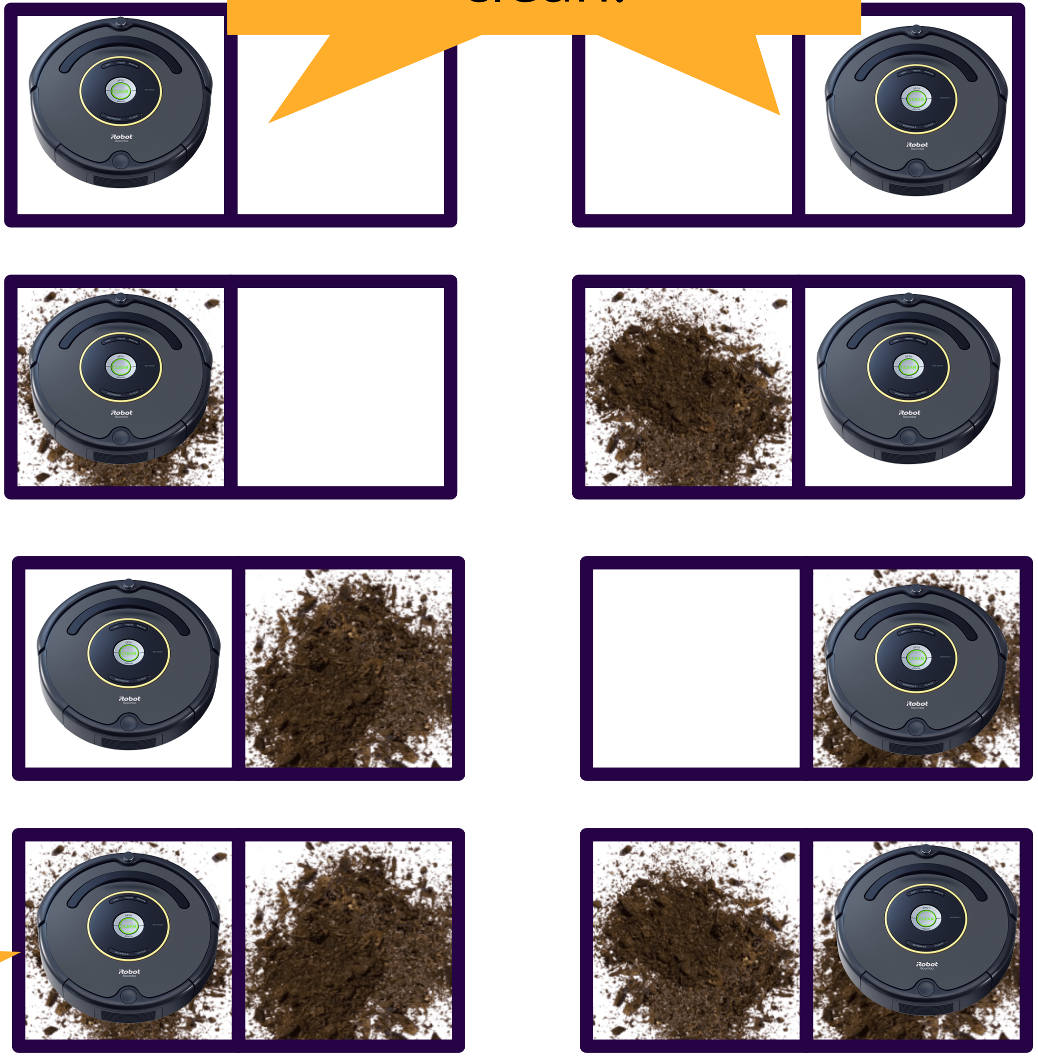
States: A state of the world says which objects are in which cells.

In a simple two cell version,

- the agent can be in one cell at a time
- each cell can have dirt or not

2 positions for agent * 2^2 possibilities for dirt = 8 states.

With *n* cells, there are $n*2^n$ states.



One state is designated as the **initial state**

Vacuum World

Actions:

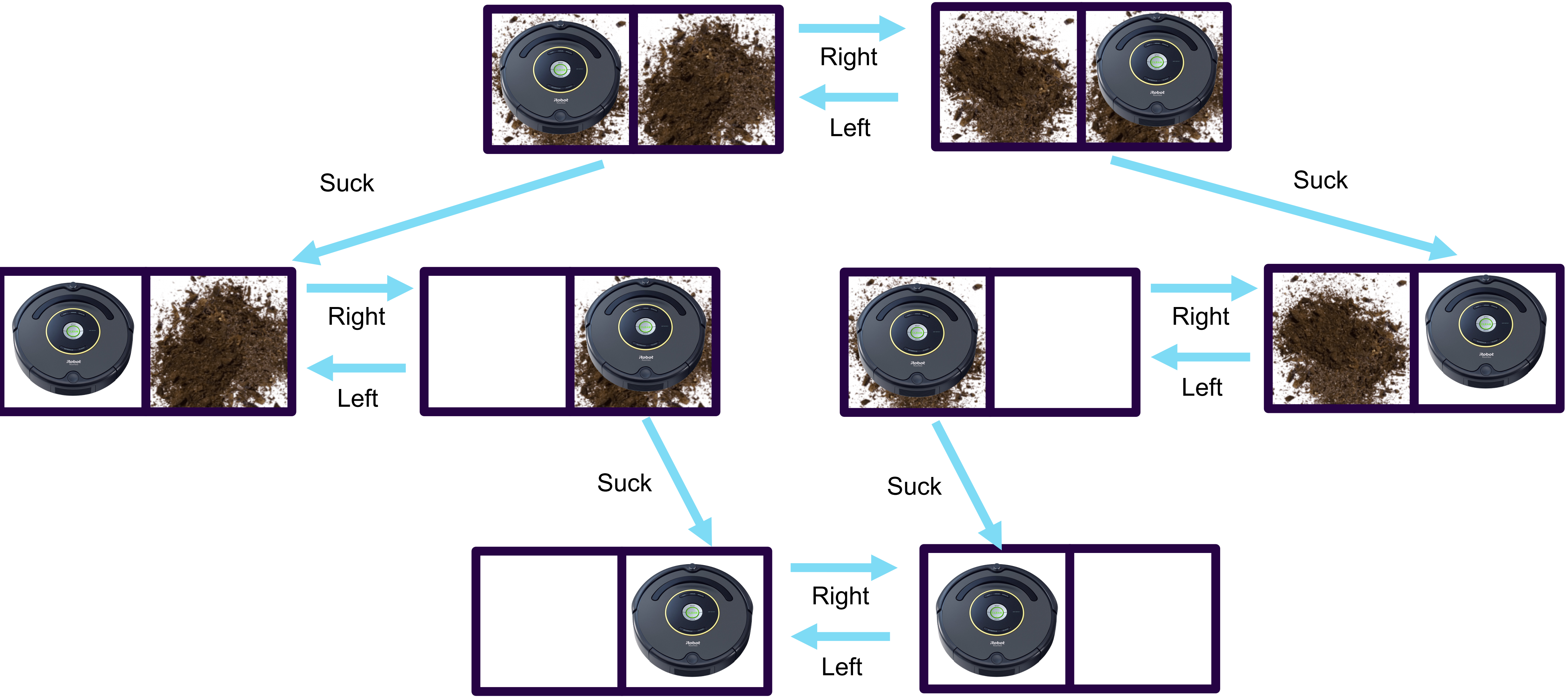
- *Suck*
- *Move Left*
- *Move Right*
- *(Move Up)*
- *(Move Down)*

Transition:

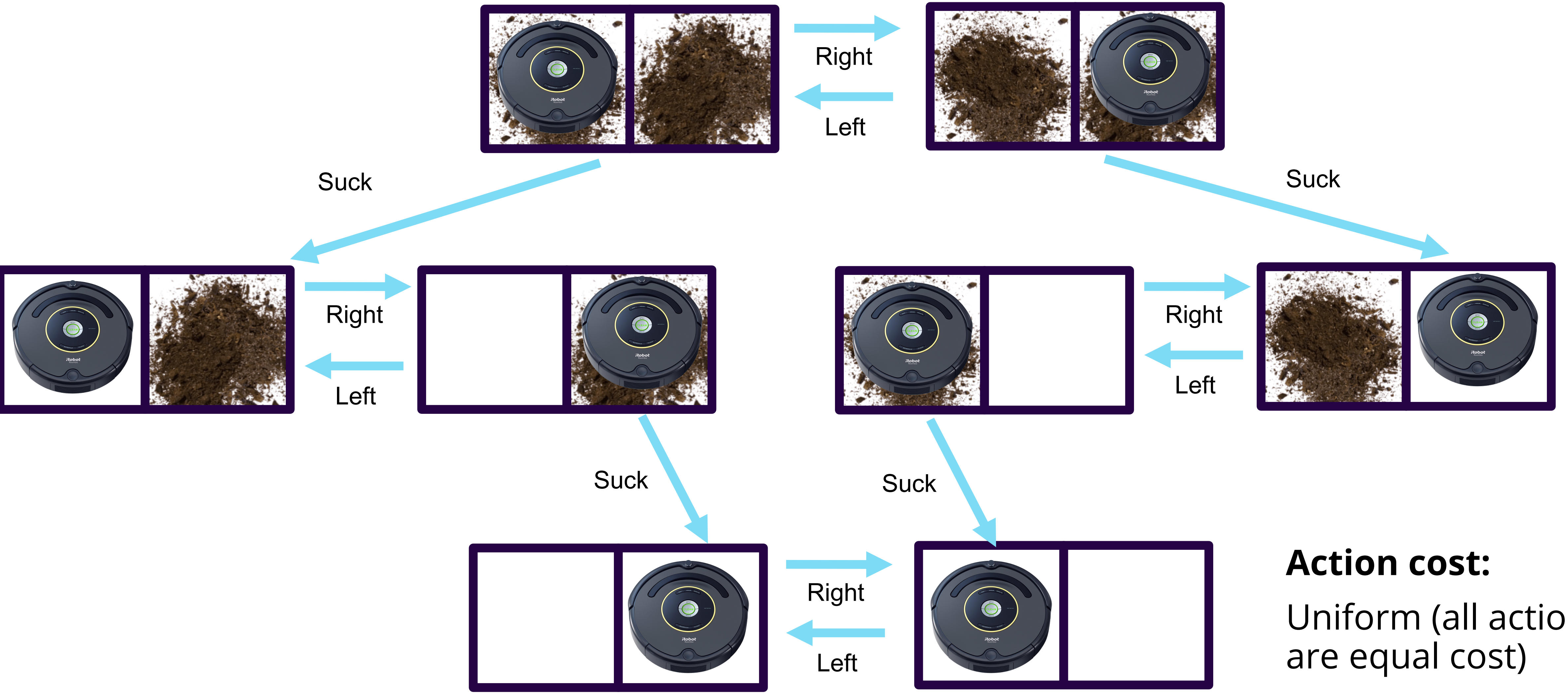
Suck – removes dirt

Move – moves in that direction, unless agent hits a wall, in which case it stays put.

Vacuum World



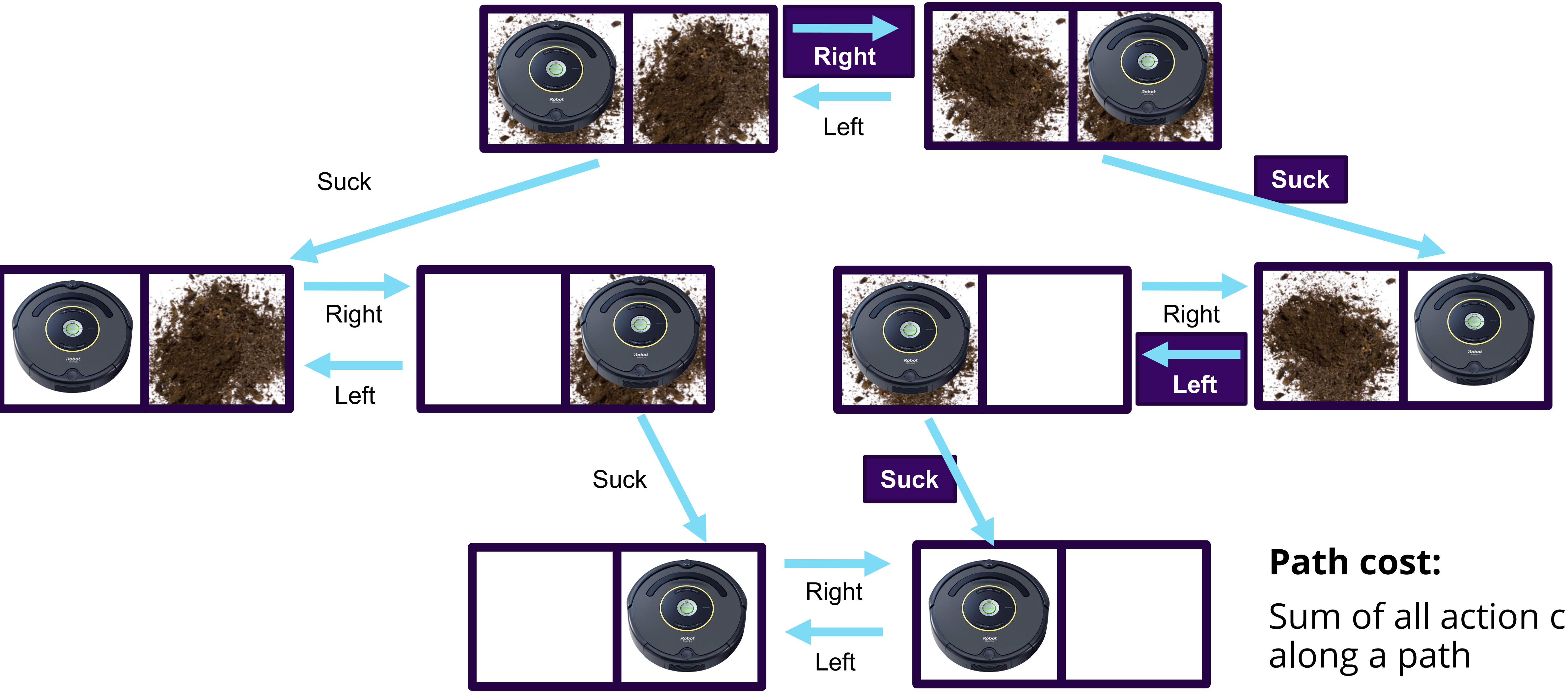
Vacuum World



Action cost:

Uniform (all actions are equal cost)

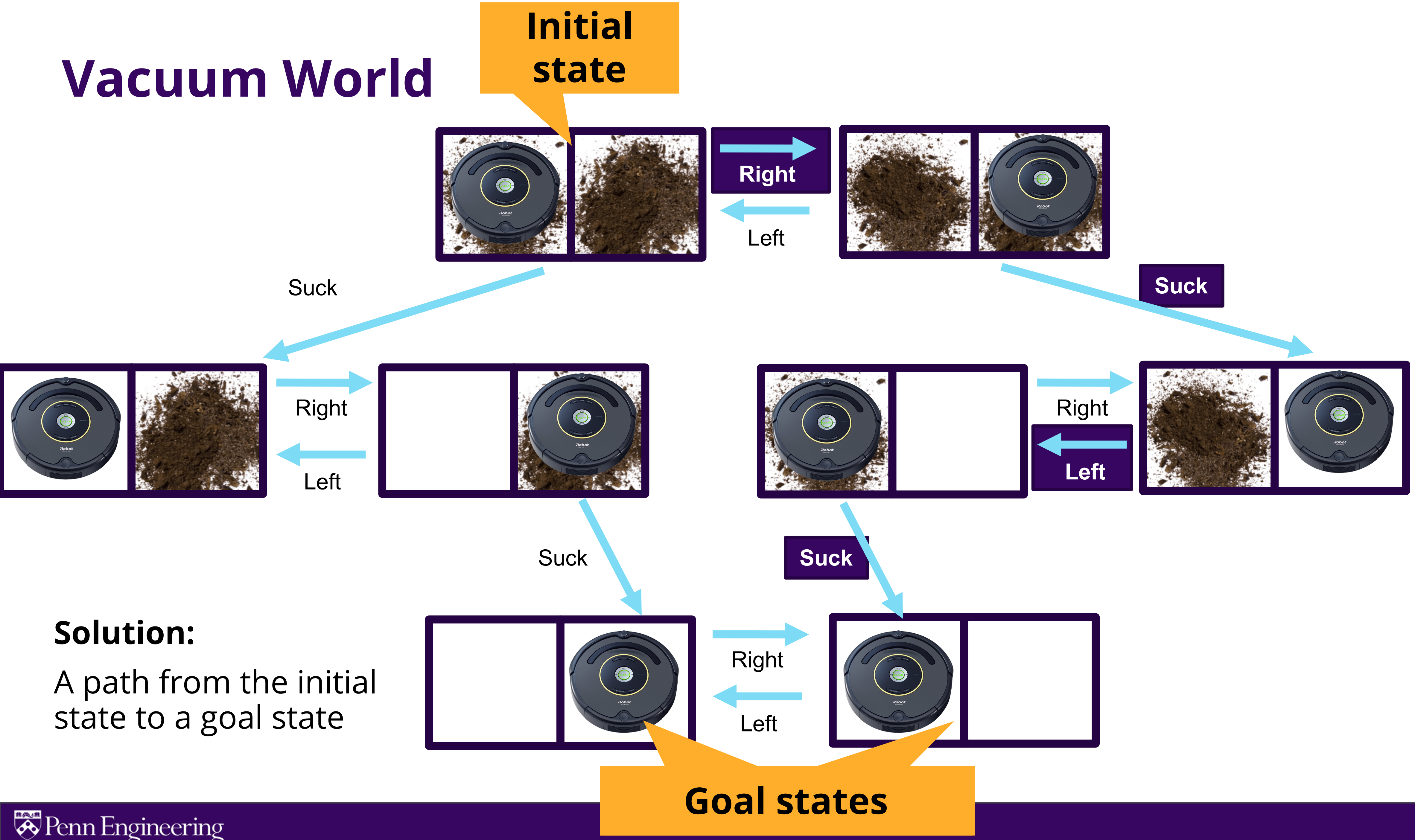
Vacuum World



Path cost:

Sum of all action costs along a path

Vacuum World



Solution:

A path from the initial state to a goal state

Search Algorithms

Useful Concepts

State space: the set of all states reachable from the initial state by *any* sequence of actions

- *When several operators can apply to each state, this gets large very quickly*
- *Might be a proper subset of the set of configurations*

Path: a sequence of actions leading from one state s_j to another state s_k

Solution: a path from the initial state s_i to a state s_f that satisfies the goal test

Search tree: a way of representing the paths that a search algorithm has explored. The root is the initial state, leaves of the tree are successor states.

Frontier: those states that are available for *expanding* (for applying legal actions to)

Solutions and *Optimal* Solutions

A *solution* is a sequence of actions from the initial state to a goal state.

Optimal Solution: **A solution is optimal if no solution has a lower path cost.**

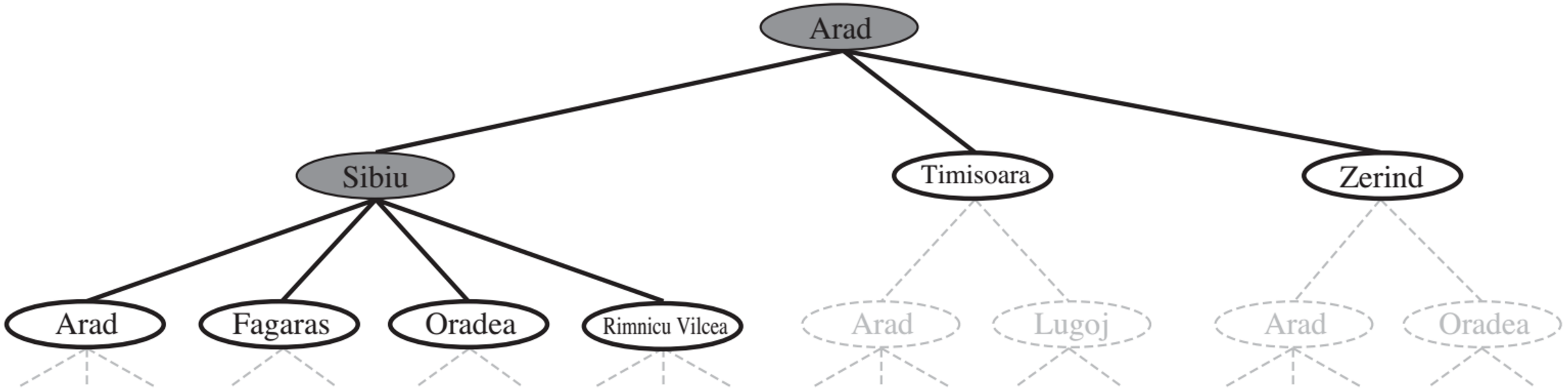
Basic search algorithms: *Tree Search*

Generalized algorithm to solve search problems

Enumerate in some order all possible paths from the initial state

- Here: search through ***explicit tree generation***
  - ROOT= initial state.
  - Nodes in search tree generated through ***transition model***
  - Tree search treats different paths to the same node as distinct

Generalized tree search



function TREE-SEARCH(*problem, strategy*) return a solution or failure

Initialize frontier to the *initial state* of the *problem*

do

if the frontier is empty then return *failure*

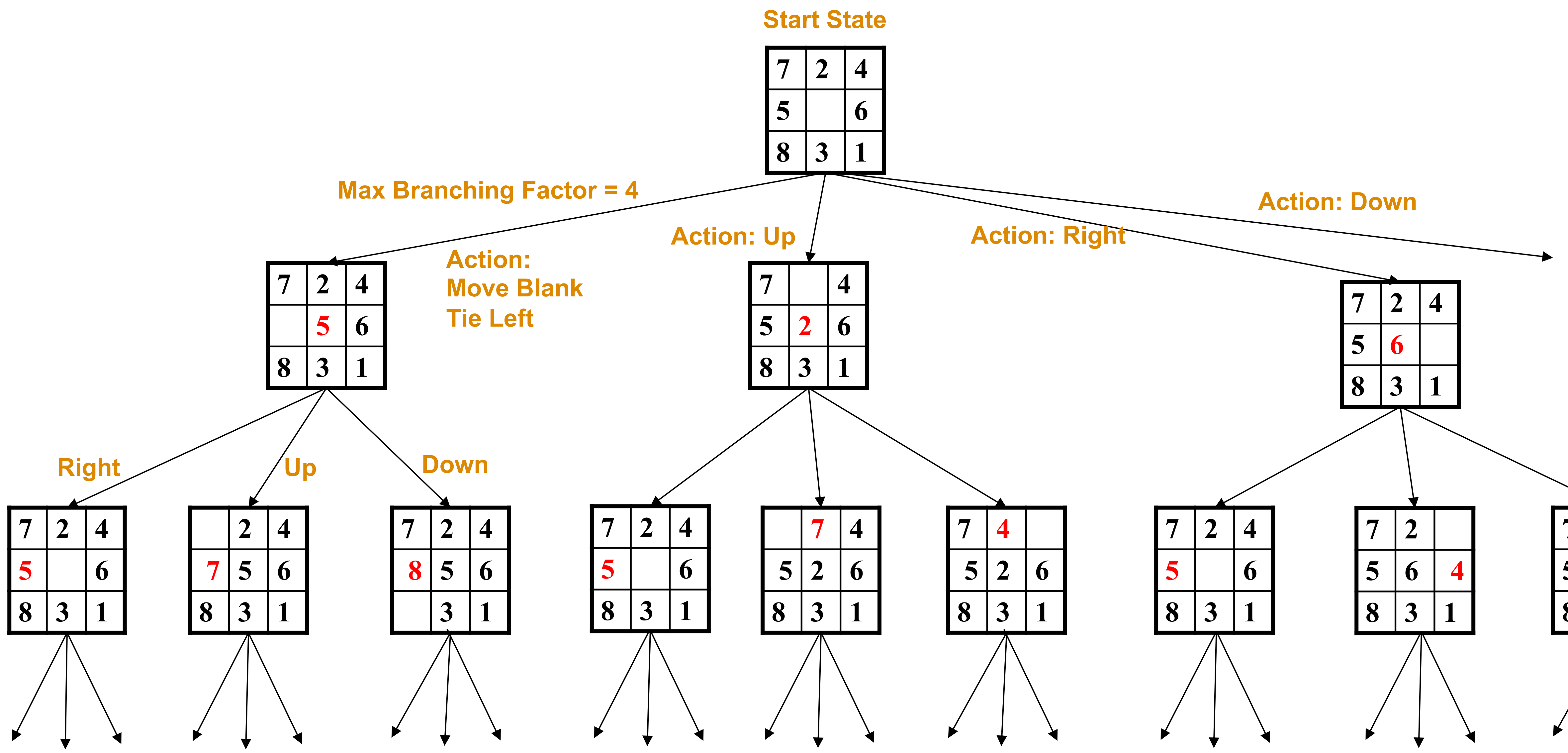
choose leaf node for expansion according to strategy & remove from frontier

if node contains goal state then return *solution*

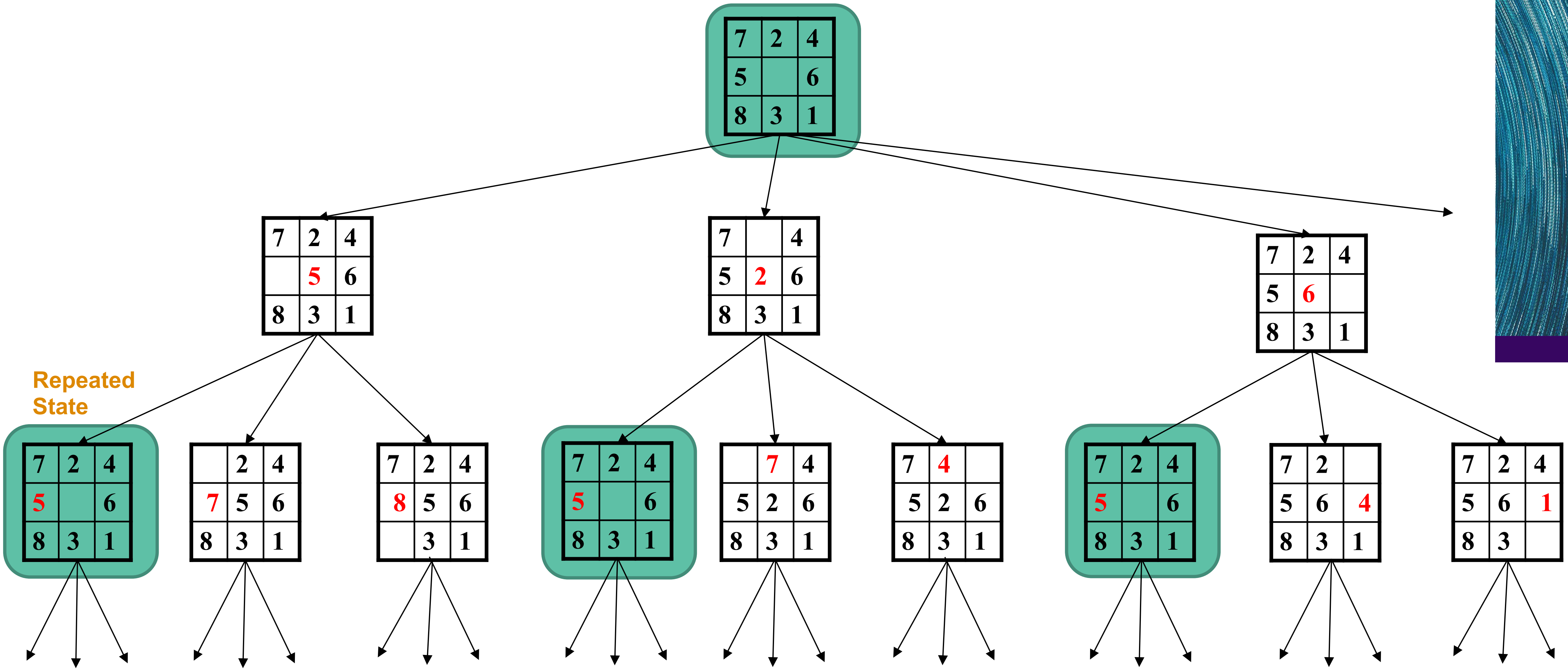
else expand the node and add resulting nodes to the frontier

The strategy determines search process!

8-Puzzle *Search Tree*



8-Puzzle *Search Tree*



Graph Search vs Tree Search

function TREE-SEARCH(*problem*) **returns** a solution, or failure
initialize the frontier using the initial state of *problem*
loop do
if the frontier is empty **then return** failure
choose a leaf nose and remove it from the frontier
if the node contains a goal state **then return** the corresponding solution
expand the chosen node, adding the resulting nodes to the frontier

function GRAPH-SEARCH(*problem*) returns a solution, or failure
initialize the frontier using the initial state of *problem*
initialize the explored set to be empty
loop do
if the frontier is empty **then return** failure
choose a leaf node and remove it from the frontier
if the node contains a goal state **then return** the corresponding solution
add node to the explored set
expand the chosen node, adding the resulting nodes to the frontier
only if not in the frontier of explored set

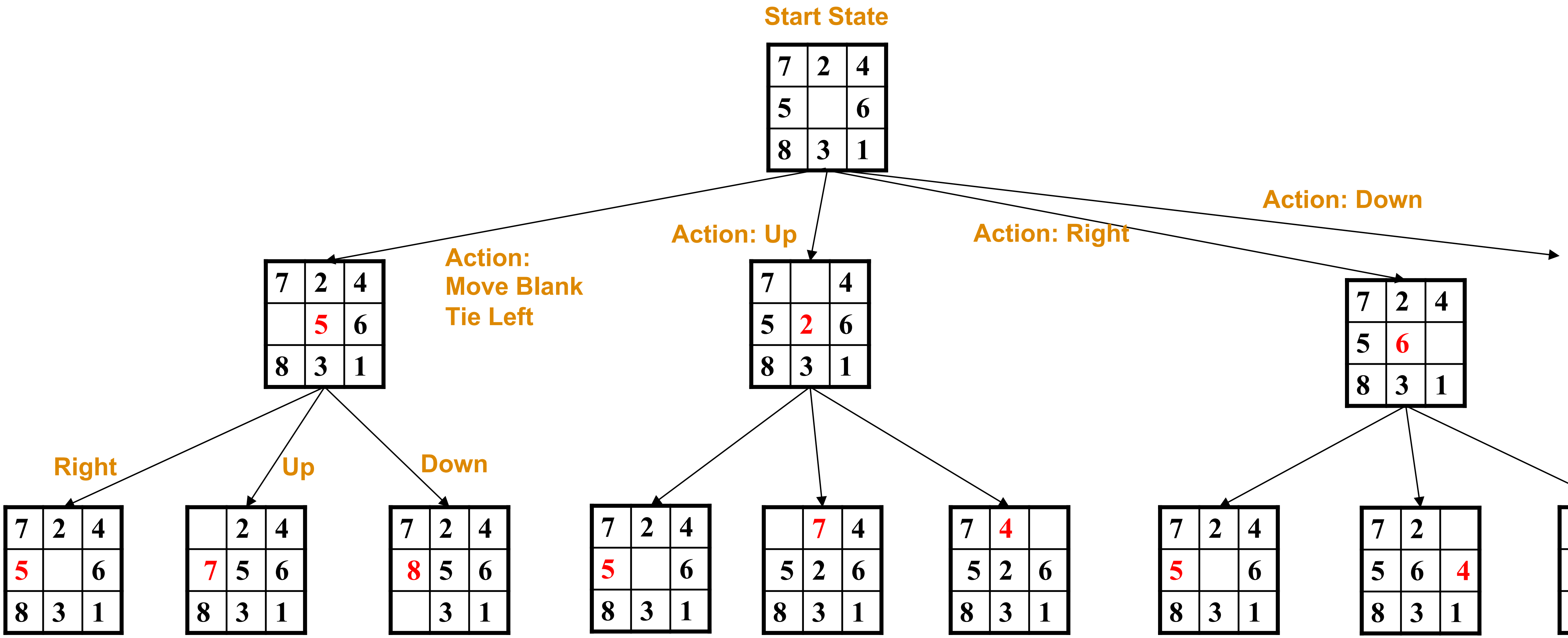
Search Strategies

Several classic search algorithms differ only by the order of how they expand their search trees

You can implement them by using different queue data structures

- **Depth-first search** = LIFO queue
- **Breadth-first search** = FIFO queue
- **Greedy best-first search** or **A* search** = Priority queue

8-Puzzle Breadth-first search



Search Algorithms

Dimensions for evaluation

- ***Completeness***- always find the solution?
- ***Optimality*** - finds a least cost solution (lowest path cost) first?
- ***Time complexity*** - # of nodes generated *(worst case)*
- ***Space complexity*** **- # of nodes simultaneously in memory** *(worst case)*

Time/space complexity variables

- *b*, *maximum branching factor* of search tree
- *d*, *depth* of the shallowest goal node
- *m*, *maximum length* of any path in the state space (potentially ∞)

Properties of breadth-first search

Complete? Yes (if *b* is finite)

Optimal? Yes, if cost = 1 per step
(not optimal in general)

Time Complexity? $1+b+b^2+b^3+\dots+b^d = O(b^d)$

Space Complexity? $O(b^d)$ (keeps every node in memory)

Time/space complexity variables

- *b*, *maximum branching factor* of search tree
- *d*, *depth* of the shallowest goal node
- *m*, *maximum length* of any path in the state space (potentially ∞)

BFS versus DFS

Time/space complexity variables

- *b*, *maximum branching factor* of search tree
- *d*, *depth* of the shallowest goal node
- *m*, *maximum length* of any path in the state space (potentially ∞)

Breadth-first

- ☑ Complete,
- ☑ Optimal
- ☒ *but* uses $O(b^d)$ space

Depth-first

- ☒ Not complete *unless m is bounded*
- ☒ Not optimal
- ☒ Uses $O(b^m)$ time; terrible if m >> d
- ☑ *but* only uses $O(b*m)$ ***space***

Exponential Space (and time) Is Not Good…

- Exponential complexity uninformed search problems *cannot* be solved for any but the smallest instances.
- *(Memory* requirements are a bigger problem than *execution* time.)

DEPTH	NODES	TIME	MEMORY
2	**110**	**0.11 milliseconds**	**107 kilobytes**
4	**11110**	**11 milliseconds**	**10.6 megabytes**
6	**10^6**	**1.1 seconds**	**1 gigabytes**
8	**10^8**	**2 minutes**	**103 gigabytes**
10	**10^{10}**	**3 hours**	**10 terabytes**
12	**10^{12}**	**13 days**	**1 petabytes**
14	**10^{14}**	**3.5 years**	**99 petabytles**

Assumes b=10, 1M nodes/sec, 1000 bytes/node

Action Castle

Art: Formulating a Search Problem

Decide:

Which properties matter & how to represent

- *Initial State, Goal State, Possible Intermediate States*

Which actions are possible & how to represent

- *Operator Set: Actions and Transition Model*

Which action is next

- *Path Cost Function*

Formulation greatly affects combinatorics of search space and therefore speed of search

Action Castle Map Navigation

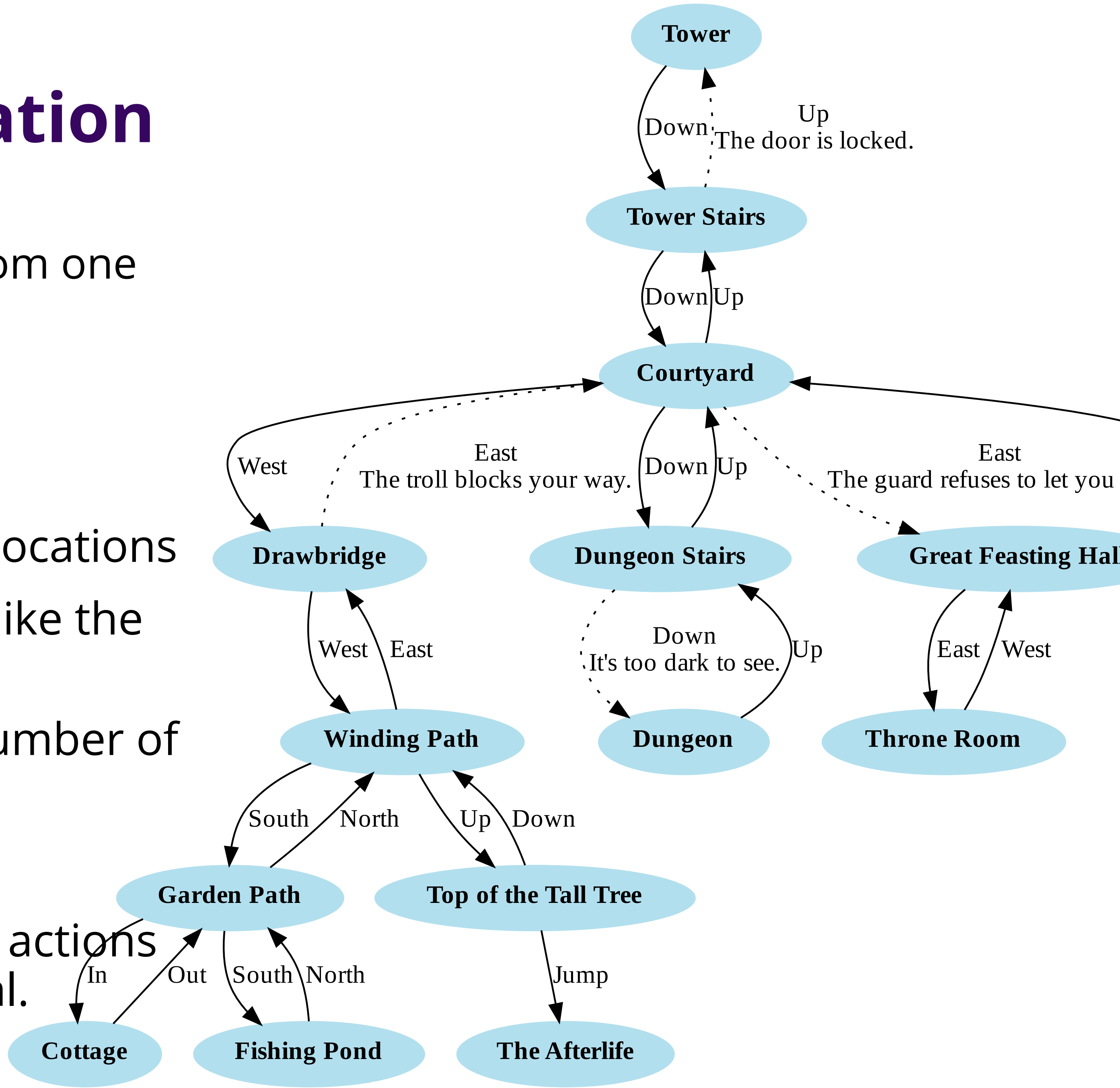
Let's consider the sub-task of navigating from one location to another.

Formulate the ***search problem***

- States: locations in the game
- Actions: move between connected locations
- Goal: move to a particular location like the **Throne Room**
- Performance measure: minimize number of moves to arrive at the goal

Find a ***solution***

- Algorithm that returns sequence of actions to get from the start sate to the goal.



```python
def BFS(game, goal_conditions):
  command_sequence = []
  if goal_test(game, goal_conditions): return co

  frontier = queue.Queue()
  frontier.put((game, command_sequence))

  visited = dict()
  visited[get_state(game)] = True

  while not frontier.empty():
    (current_game, command_sequence) = frontier.get()
    current_state = get_state(current_game)
    parser = Parser(current_game)
    available_actions = get_available_actions(current_game)

    for command in available_actions:
      # Clone the current game with its state
      new_game = copy.deepcopy(current_game)
      # Apply the command to it to get the resulting state
      parser = Parser(new_game)
      parser.parse_command(command)
      new_state = get_state(new_game)
      # Update the sequence of actions that we took to get to the resulting state
      new_command_sequence = copy.copy(command_sequence)
      new_command_sequence.append(command)
      if not new_state in visited:
        visited[new_state] = True
        if goal_test(new_game, goal_conditions):
        frontier.put((new_game, new_command_sequence))
  # Return None to indicate there is no solution.
  return None
```

The frontier tracks order of unexpanded search nodes. Here we're using a FIFO queue

The visited dictionary prevents us from revising states.

TODO: implement get_state()

get_available_actions() to return all commands that could be used here.

TODO: implement get_available_actions()

The parser can execute this command to get the resulting state.

Check to see if this state satisfies the goal test, if so, return the command sequence that got us here.

TODO: implement goal_test()

```python
def BFS(game, goal_conditions):
  command_sequence = []
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```

Tip: We can store multiple objects on the frontier as a tuple.

Tip: To be used a key in the dictionary get_state() must return an immutable object

Tip: use deepcopy here

Tip: For BFS, apply the goal test before putting the new item on the frontier

Action Castle

Let's consider the full game.

Actions

Start State

Transitions

State Space

Goal test

Actions

Go

Move to a location

Get

Add an item to inventory

Special

Perform a special action with an item like “Catch fish with pole”

~~**Drop**~~

~~Leave an item in current location~~

State Info

Location of Player

Items in their inventory

Location of all items / NPCs

Blocks like

- **Troll guarding bridge,**
- **Locked door to tower,**
- **Guard barring entry to castle**

My Solution

```
goal_conditions = {"at_location" : "Throne Room",
                   "inventory_contains" : "crown (worn)"}

game = build_game()
solution = BFS(game, goal_conditions)
print("SOLUTION:", solution)
```

```
---
Found solution at depth 36.
Expanded 4138 nodes. Trimmed 18632 nodes.
There are 83 nodes on the frontier.
```

```
solution
```

```
['get pole',
 'go out',
 'go south',
 'catch fish with pole',
 'go north',
 'pick rose',
 'go north',
 'go up',
 'get branch',
 'go down',
 'go east',
 'give the troll the fish',
 'go east',
 'hit guard with branch',
 'go east',
 'get candle',
 'go west',
 'go down',
 'light lamp',
 'go down',
 'light candle',
 'read runes',
 'get crown',
 'go up',
 'go up',
 'get key',
 'go up',
 'unlock door',
 'go up',
 'give rose to princess',
 'propose to the princess',
 'wear crown',
 'go down',
 'go down',
 'go east',
 'go east']
```

Classical Planning

AIMA Chapter 11

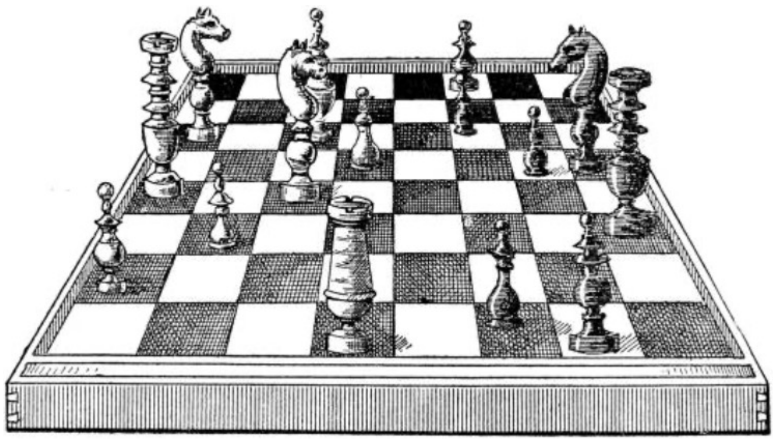
Classical Planning

The task of finding a sequence of action to accomplish a goal in a deterministic, fully-observable, discrete, static environment.

If an environment is:

- **Deterministic**
- **Fully observable**

The solution to any problem in such an environment is a fixed sequence of actions.



In environments that are

- **Nondeterministic** or
- **Partially observable**

The solution must recommend different future actions depending on the what percepts it receives. This could be in the form of a *branching strategy*.

Representation Language

Planning Domain Definition Language (PDDL) express **actions** as a **schema**

```
(define (domain action-castle)
   (:requirements :strips :typing)
   (:types player location direction item)

   (:action go
      :parameters (?dir - direction ?p - player ?l1 - location ?l2 - location)
      :precondition (and (at ?p ?l1) (connected ?l1 ?dir ?l2) (not (guarded ?l2)))
      :effect (and (at ?p ?l2) (not (at ?p ?l1)))
   )

   (:action get
      :parameters (?item - item ?p - player ?l1 - location )
      :precondition (and (at ?p ?l1) (at ?item ?l1))
      :effect (and (inventory ?p ?item) (not (at ?item ?l1)))
   )

   ction drop
      :parameters (?item - item ?p - player ?l1 - loc
      :precondition (and (at ?p ?l1) (inventory ?p ?ite
      :effect (and (at ?item ?l1) (not (inventory ?p ?i
   )

)
```

Action name

Variables

Preconditions

Effects

Preconditions and effects are **conjunctions** of logical sentences

These logical sentences are **literals** – positive or negated atomic sentences

State Representation

In PDDL, a **state** is represented as a **conjunction** of logical sentences that are **ground atomic fluents**. PDDL uses **database semantics.**

Ground means they contain no variables

Atomic sentences contain just a single predicate

Fluent means an aspect of the world that can change over time.

Closed world assumption. Any fluent not mentioned is false. Unique names are distinct.

Action Schema
has variables

```
(:action go
   :parameters (?dir - direction ?p - player ?l1 - location ?l2 - location)
   :precondition (and (at ?p ?l1) (connected ?l1 ?dir ?l2) (not (guarded ?l2)))
   :effect (and (at ?p ?l2) (not (at ?p ?l1)))
)
```

State Representation
arguments are constants
fluents may change over time

```
(:init
   (connected cottage out gardenpath)
   (connected gardenpath in cottage)
   (connected gardenpath south fishingpond)
   (connected fishingpond north gardenpath)
   (at npc cottage)
)
```

Successor States

A **ground action** is **applicable** if if every positive literal in the precondition is true, and every negative literal in the precondition is false

Ground Action
no variables

```
(:action go
    :parameters (out, npc, cottage, gardenpath)
    :precondition (and (at npc cottage) (connected cottage out gardenpath))
    :effect (and (at npc gardenpath) (not (at npc cottage)))
)
```

Initial State

```
(:init
    (connected cottage out gardenpath)
    (connected gardenpath in cottage)
    (connected gardenpath south fishingpond)
    (connected fishingpond north gardenpath)
    (at npc cottage)
)
```

Negative literals in the effects are kept in a **delete list**, and positive literals are kept in an **add list**

Result
New state reflecting the effect of applying the ground action

```
(connected cottage out gardenpath)
(connected gardenpath in cottage)
(connected gardenpath south fishingpond)
(connected fishingpond north gardenpath)
(at npc gardenpath)
```

Domains and Problems

Domain

Set of Action Schema

```
(define (domain action-castle)
   (:requirements :strips :typi
   (:types player location direction item)

   (:action go
      :parameters (?dir - direction ?p - player
                   ?l1 - location ?l2 - location)
      :precondition (and (at ?p ?l1) (connected ?l1 ?dir ?l2))
      :effect (and (at ?p ?l2) (not (at ?p ?l1)))
   )

   (:action get
      :parameters (?item - item ?p - player ?l1 - location )
      :precondition (and (at ?p ?l1) (at ?item ?l1))
      :effect (and (inventory ?p ?item) (not (at ?item ?l1)))
   )

   (:action drop
      :parameters (?item - item ?p - player ?l1 - location )
      :precondition (and (at ?p ?l1) (inventory ?p ?item))
      :effect (and (at ?item ?l1) (not (inventory ?p ?item)))
   )

)
```

Problem

```
(define (problem navigate-to-location)
   (:domain action-castle)

   (:objects
      npc - player
      cottage gardenpath fishingpond  - location
      in out north south eas
   )

   (:init
      (connected cottage out gardenpath)
      (connected gardenpath in cottage)
      (connected gardenpath south fishingpond)
      (connected fishingpond north gardenpath)
      (at npc cottage)
   )

   (:goal (and (at npc fishingpond)))
)
```

Initial State

Goal

Algorithms for Classical Planning

We can apply **BFS** to the **initial state** through possible states looking for a **goal**.

An advantage of the **declarative representation** of action schemas is that we can also **search backwards**.

Start with a goal and work backwards towards the initial state.

In our Action Castle example, this would help us with the branching problem that the ***drop*** *action introduced. If we work backwards from the goal, then we realize that we don't ever need to drop an item for the correct solution.*